

Frequency tuning of the whispering gallery modes of silica microspheres for CQED and spectroscopy

Wolf von Klitzing*, Romain Long, Vladimir S. Ilchenko†, Jean Hare, Valérie Lefèvre-Seguin

*Laboratoire Kastler Brossel, Département de Physique de l'Ecole Normale Supérieure,
24 Rue Lhomond, 75231 Paris Cedex 05, France*

Abstract

We have tuned the whispering gallery modes of a fused silica microresonator over nearly 1 nm at 800 nm, i. e. over 0.5 FSR or 10^6 linewidths of the resonator. This has been achieved by a new method based on the stretching of a two-stem microsphere. The devices described below will permit new Cavity-QED experiments with this high-Q optical resonator when it is desirable to optimize its coupling to emitters with given transition frequencies. The tuning capability demonstrated here is compatible with both UHV and low temperature operation, which should be useful for future experiments with laser cooled atoms or single quantum dots.

Light in a dielectric microsphere can be confined to so called whispering gallery modes (WGMs). The mode volume can be as low as a few hundred cubic wavelengths with quality factors above 10^9 for fused silica.¹⁻³ Due to these advantageous properties, glass microspheres have attracted much interest in various fields ranging from unusual lasers^{4,5} over CQED,^{6,7} spectroscopy,⁸ and non-linear electrodynamics.^{1,9} So far the main default of the microspheres has been their fixed frequency. Accidental coincidences between an atomic line and the fundamental transverse whispering gallery mode are extremely rare both because the free spectral range (FSR) of a microsphere is very large, of the order of 1 THz, and because the resonance linewidth is very small, about 300 kHz. Tuning the whispering gallery mode spectrum whilst preserving their high Q's is therefore an important experimental challenge.

A useful device should fulfill the following conditions. The tuning range should be about the free spectral range (FSR) so that a mode with the desired transverse distribution of light can be tuned into resonance with, e.g., an atomic transition. The device should be exceedingly stable because a change of only 10^{-7} of the desired tuning range would already shift the WGMs by one line width. Good access to the sphere must be guaranteed in order to enable coupling light in and out of the sphere and also to approach the sample to the sphere it is to interact with (quantum dots, cold atoms, etc ...). Furthermore the device should be readily producible and affordable. This is especially important for potential applications,

e.g. as gas detectors. Ultra-high vacuum compatibility is also required if one wishes to couple laser-cooled atoms to a microsphere⁷. In some cases, it may be desirable to operate the tunable microsphere at liquid helium temperatures.

There are two methods to tune the modes: temperature and strain^{10,11,2}. At first order, both affect the mode resonance through the simple relation: $\Delta\nu/\nu = -\Delta a/a - \Delta N/N$, where a is the radius of the sphere and N its refractive index. The temperature dependence of the modes is about -2.5 GHz/K so that it can only be used for fine tuning purposes. Strain tuning on the other hand can cover a whole FSR if one achieves $\Delta\nu/\nu \simeq 1/l$. For a 50 micrometers sphere, this means a deformation of about 0.2% in the equatorial region and an axial strain of about 1%, which is still compatible with the elastic deformation tolerated by fused silica, as demonstrated by experiments performed on silica fibers¹². The first demonstration device used on a microsphere was designed to compress the sphere with piezo-driven pliers¹³. About one quarter of the sphere protruded from the device thus allowing coupling to the WGMs. For a sphere of a diameter of 160 μm , tuning over 150 GHz, nearly one half of an FSR, was achieved. However, access to the sphere was very limited and the device was not usable for spheres smaller than 100 μm . This precludes experiments on bulk samples with quantum dots (access), for instance, and on lasing in doped silica microspheres (size).

Here a new method is presented in which the strain is applied to the sphere by stretching it. Advances in the ability to manipulate silica glass with a CO₂ laser allow us to produce spheres with two stems, one on each pole. The strain on the microsphere can now be exerted by simply pulling on the ends of the two stems which should not be too thin, so as to produce enough strain on the sphere's equator. With a sphere having twice or three times the diameter of the stems, the desired stretching of the sphere can still be reached within the elastic limit of silica.

We have made two different devices. Both of them give access to a half space around the sphere, the other half being occupied by the coupling optics. Device #1 is a modified version of the squeezer mentioned above. The double-stemmed sphere is produced as follows. As in our previous experiments, the starting material is the core of an optical fiber or a thin fiber pulled in a flame

from a rod of pure synthetic silica. The silica fiber to be melted and the CO₂ laser beam are both vertical. The fiber is maintained vertical with a 5–10 mg weight attached to its lower end. The laser beam (diameter ≈ 3 mm) is projected upwards through a focusing lens. The short focal length of 25 mm creates a small focal spot (diameter ≈ 60 μ m) and a strong vertical gradient in the intensity of the infrared radiation. As a result, the fiber hanging down will only melt near the focus. Due to surface tension forces, a microsphere will form and remain attached to the non-heated parts of the wire upon cooling down. Its ellipticity can be below 1%. Shortly after its fabrication, the double-stemmed microsphere is glued in between the jaws of the tuning device. Spheres with a diameter down to about 60 μ m having a stem diameter of about 30 μ m can be used in this device.

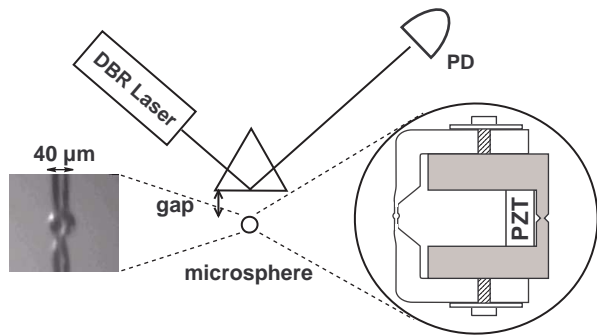


Fig. 1. Simplified sketch of the experimental set-up. The WGM modes of the microsphere are excited through a high index prism by frustrated total internal reflection. The resonances are detected as dips on the laser light intensity coming out of the prism. The right-side insert shows a side-view of the stretching device. The left-side insert is a CCD image of a double-stemmed microsphere as seen through our microscope.

The second device has been designed to work in a UHV environment on smaller spheres. It consists of a U shaped base made from bronze which can be opened and closed with a screw and a vacuum compatible low voltage PZT stack. As shown in Fig. 1, two rods of pure silica bent in a flame are fixed with screws on the jaws of the device so that they nearly meet at mid-height. Their tips are then ground to the shape of pyramids with a tip to tip distance of 400 μ m. Next the CO₂ laser is used to weld a short piece of silica fiber across the gap. The sphere is then formed by melting the center of the fiber with two counter-propagating CO₂ laser beams while the initial PZT voltage is slowly relaxed. This production method has been used in an open set-up but the last step could be performed directly in a high vacuum chamber when necessary. Whatever the

fabrication technique, the fusion process is always observed in a stereomicroscope with a video camera and the alignment of the CO₂ laser is carefully controlled by mounting the device and the laser focusing lenses each on 3D translations stages. Care is taken to eliminate residual tensions in the silica glass by gentle heating in the CO₂ laser before and after the fusion process. The power of the CO₂ laser is precisely controlled to avoid any excess heating which would cause unwanted recrystallization of the silica and/or sublimation. This allows us to produce a microsphere with two stems as short and thick as possible. This ensures maximum strain and stability of the sphere (both mechanical and thermal). A typical 40 μ m microsphere is shown in the left-side insert of Fig. 1.

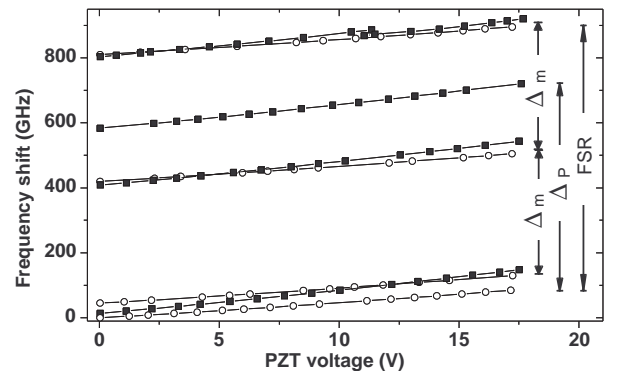


Fig. 2. Frequency shift versus PZT voltage for several TM (■) or TE (○) whispering gallery modes. Frequency intervals, characterizing the WGM spectrum of the microsphere are also shown, namely the free-spectral range FSR, the separation Δ_P between modes differing only in their polarizations, and Δ_m the frequency difference due to a change by one unit of m . TM modes are, as expected, more sensitive to stress than TE modes by a factor 1.6.

The tuning of the whispering gallery modes was studied with a set-up described previously.² Light from a diode laser is coupled into the sphere through a SF11-glass prism. We studied first device #1 using a 800 nm diode laser stabilized with an external grating which had a maximum continuous tuning range of 30 GHz with a linewidth of about 300 kHz. Like in Ref. 13, the average tuning range of the modes in the sphere has been assessed by continuously increasing the voltage at the PZT and observing the modes passing through the frequency window scanned by the diode laser. Assuming that there is no strong non-linearity in the strain with respect to the PZT voltage the maximum tuning range of this device was found to be 150 GHz, i.e about half of an FSR for the 200 μ m sphere under study. The stability of the WGM frequency at a fixed PZT voltage was

excellent: over a number of days, the modes drifted by less than 10 GHz. On a short time scale, the WGM frequency fluctuations were fully correlated to the measured temperature variations. As usual in air, the modes kept their initial Q value of about 10^8 for several days.

The second device was studied with a narrow linewidth tunable DBR diode laser (Yokogawa YL78XNL/S). The laser mode wavelength of these diodes can be tuned continuously over 1 nm by simultaneously changing the diode and the grating currents. This allowed us to follow the same WGM mode over 400 GHz. Fig. 2 shows the frequency shift of several WGM modes versus the PZT voltage for a 80 μm sphere. Here the voltage range was limited on purpose to stay within the elastic limit and hence well below the maximum tuning range. We checked on the observed shift that the deformation was perfectly reversible upon decreasing the PZT voltage. The stability of the deformation was excellent, as well as the repeatability of these results. The well-known quasi-periodicity of the WGM mode spectrum is exhibited by marking three characteristic frequency differences: FSR = 810 GHz is the free spectral range of the sphere (diameter 80 μm), $\Delta_P = 580$ GHz is the expected interval between TE and TM modes with the same quantum numbers, n , l , m , and finally $\Delta_m = 375$ GHz is the interval between modes which only differ by one unit in m , the azimuthal order number.¹⁴ It corresponds to an effective ellipticity of about 50%, in agreement with a CCD image of the sphere. The slope of the lines is 5 GHz/V for TE modes and 8 GHz/V for TM modes. The TM/TE slopes ratio is 1.6. It is close to 1.75, the ratio expected for a perfect cylinder¹². This is consistent with the large ellipticity of this resonator. The axial strain derived from these measurements is $\epsilon \simeq 6 \cdot 10^{-5}$ per Volt. This yields an overall deformation of the sphere with its two stems of 0.25 μm for 10 V applied on the PZT, to be compared to the 0.5 μm /10 V specification of the stack.

Fig. 3 shows the maximum excursion reached on this 80 μm sphere for a TE and TM whispering gallery mode. When the PZT voltage was further increased up to 42 V, the onset of plastic deformation was observed as a slip of the frequency of the modes shortly before one of the stems severed.

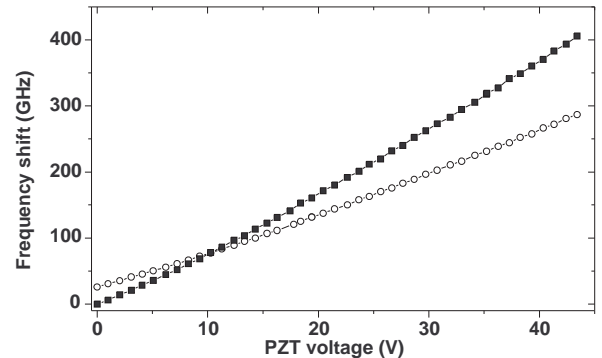


Fig. 3. Frequency shift for a pair of TM (■) and TE (○) modes followed continuously over the maximum applied stress.

To summarize, we have developed two devices which both have allowed us to tune whispering gallery modes over half a FSR. In both cases the maximum quality factor of $Q=10^9$ can be reached reproducibly and is preserved for a number of days under standard laboratory conditions. Device # 1 is easier to make and it is more appropriate to work with moderate size spheres (60 to 500 micrometers) while device # 2 is compatible with smaller spheres although it needs more skill to get a small ellipticity. Now that microspheres can be considered as tunable resonators, we believe that the devices presented here open the way to several applications like single mode microlasers, tunable filters, gas detectors and other cavity QED experiments with adsorbed molecules, cold atoms grazing the sphere or quantum dots in semiconductor samples.

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15. The precise design of the device should give a lever effect of about 5 at the jaws of the device. It helps to compensate the imperfection of the device in the region where the final welding of the upper stem was made.